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# SUPPLEMENT TO THE REPORT ON THE RESULTS ACHIEVED WITH SEAS' EXPERIMENTAL MILL

J. Juul

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16. Abstract Several points discussed in the report on results achieved with SEAS' experimental windmill (see NASA TT F-15,515) are elaborated on: greatest efficiency of the mill was obtained at a wingtip velocity of 38 m/s;effects caused by wind pressure should not exceed 800 kg/cm$^2$ in any part of the wing or tower, and effects caused by gravity in the wings should not exceed 200-300 kg/cm$^2$. Experience has shown that the optimal height of the support tower should be from 18-24 m. A history of the Dutch windmill's use and its construction, and also of various modern experimental wind power stations in various parts of the world is given. Costs of building wind power stations are discussed.

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SUPPLEMENT TO THE REPORT ON THE RESULTS ACHIEVED WITH SEAS' EXPERIMENTAL MILL

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To the report which was submitted to the OEEC meeting in London, 7-10 November 1950, in Working Party No. 2, Wind Power, can be added the following supplementary information concerning results obtained since then with SEAS' experimental mill. /65*

The report can be found published in OEEC Report No. 7, of the meeting held in London, on pp. 61-70, and in *Elektroteknikeren*, No. 1, of 7 January 1951, pp. 5-12.

In the introduction to the report, under Points 1-6, the objectives are stated that were the basis for the construction and testing of the experimental mill.

There are no additional remarks concerning the points mentioned under 1-3.

In regard to point 4, concerning the determination of the possible annual production, it can be noted that the experimental mill has been in continuous operation in the following periods: June, July and December 1950, and January, February, March, May, June, July and August 1951. There have, however, been occasional stops during the period mentioned due to testing of various relays, replacements and adjustments.

During the time the mill was out of operation, the energy it could have produced was computed according to the measured wind velocity, and the result added to the kWh measured on

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*Numbers in the margin indicate pagination in the foreign text.

the kWh meter. This energy made up about 10% of the measured energy.

In calculating the mill's efficiency, its output is related to the natural work capacity of the wind. This is computed by the formula for energy of motion a = $(m \cdot v^2)/2$, where V is the wind velocity and M the mass [sic].

The mass is the weight of the quantity of air moved by the wind velocity divided by the constant of the speed of gravity. Computed in kg·m·sec, we obtain:

$$\text{kg} \cdot \text{m} \cdot \text{sec} = \frac{1{,}22}{9{,}81} \times \frac{V^2}{2} \times \frac{\pi}{4} \times D^2 \times V$$

where D is the diameter of the mill's wingspan and 1.22 the weight of air in kg/$m^3$ at 15°C.

Since the wind's energy of motion is to be transmitted to elements in motion, only a portion of the wind's velocity can be utilized. There is therefore a point in the wind's retardation which yields the most power. By calculating a sufficiently large number of examples, we will find that the most favorable retardation factor is 0.6.

After conversion, we thus obtain HK = $\frac{1{,}22}{9{,}81} \times \frac{V^2}{2} \times \frac{D^2\pi}{4} \times$ or HK = $V \times 0{,}6 \times \frac{1}{75}$ eller HK = $0{,}000388 \times D^2 \times V^3$ corresponding to KW = $0{,}000285 \times D^2 \times V^3$.

According to the last-mentioned formula, the total wind energy which can affect the mill's wings is computed.

The mill cannot, however, like all other power machines, utilize the applied energy to the full, but has an efficiency factor which is dependent upon the construction of the wings and their velocity in relation to the wind velocity.

The mill is coupled by means of a fixed gear to an asynchronous AC generator capable of continuously delivering 13 kW.

The gear ratio between the generator and the main axle is adjusted so that the wind velocity becomes 38 m/s, which has proved to be the most advantageous under the given conditions.

The magnitude of the output the mill can produce is determined by reading a directly indicating precision wattmeter inserted in the generator circuit, simultaneously reading the wind velocity or a directly indicating anemometer mounted at the same height as the mill's main axle, which indicates the immediate wind velocity. By recording simultaneous readings during periods when the wind was of steady velocity, curves 2 and 4 shown in Fig. 3a are determined.

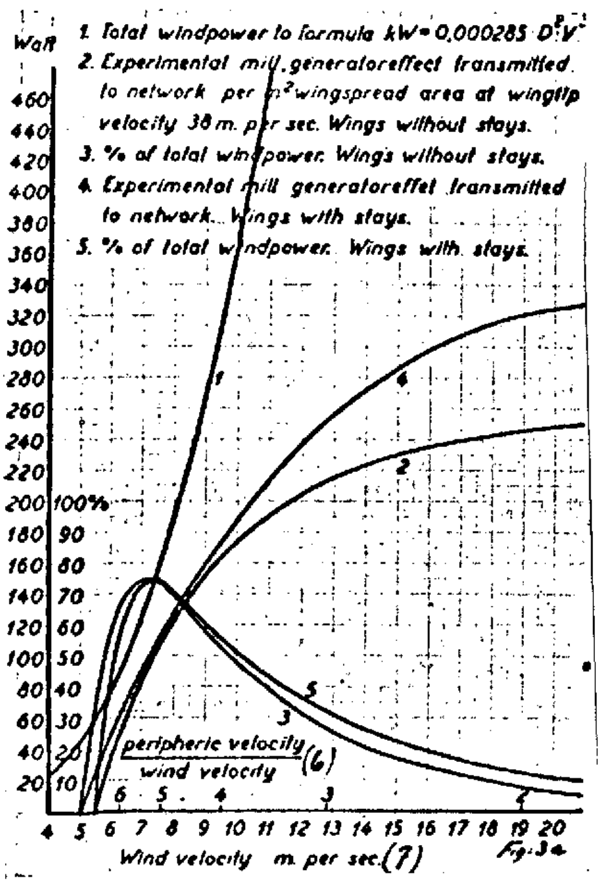



Fig. 3a.

Until 1 May, the experimental mill was equipped with two wings. In May, the wingspan was rebuilt and provided with an additional two small wings, in order to achieve the bracing of the main wings in the direction of revolution, which proved to be necessary. An account will be given of this condition under point 6.

The addition of the bracing wings proved to have an influence upon the mill's characteristics. In Fig. 3a, curve 2 shows the mill's output before the bracing wings were /66 added, and in curve 4 is shown the output after the addition of the bracing wings.

It appears from this that these wings increase the mill's power noticeably in weak and in strong winds, while at wind velocities of from 6.5 to 10 or 11 m/s, there is no appreciable difference in output, and since the most frequent winds are within this region, the addition of the bracing wings has not meant any noticeable increase of energy developed, in kWh.

Table 1 shows the production per month. Column 2 gives the production of the mill. Column 2 is the computed production according to average wind velocity per hour multiplied by the generator's output, according to curve 2 in Fig. 3a.

TABLE.

| | | Estimated production acc. to average wind velocity | Production of the experimental mill | Difference | | | |
|---|---|---|---|---|---|---|---|
| | | | | + | | ÷ | |
| | | kWh. | kWh. | kWh. | % | kWh. | % |
| Jun | 1950 | 1.545 | 1.824 | 279 | 18,0 | | |
| Jul | — | 2.092 | 2.009 | | | 83 | 4,0 |
| Dec | — | 1.623 | 1.810 | 187 | 11,5 | | |
| Jan | 1951 | 1.081 | 1.827 | 746 | 69,0 | | |
| Feb | — | 1.373 | 1.937 | 564 | 41,0 | | |
| Mar | — | 3.048 | 2.915 | | | 133 | 4,4 |
| Maj | — | 1.472 | 1.815 | 343 | 23,3 | | |
| Jun | — | 1.213 | 821 | | | 392 | 22,3 |
| Jul | — | 1.890 | 1.666 | | | 224 | 12,0 |
| Aug | — | 939 | 1.256 | 317 | 34,0 | | |
| | | 16.278 | 17.880 | | 10 | | |

At the meetings in OEEC Group 2, Wind Power, it was discussed to what degree one could determine the energy which can be taken out of the wind with sufficient accuracy, by means of wind velocity measurements determined as an average wind velocity per hour.

Professor P. Santorini of Athens, in particular, has criticized the method on the basis of the observation that the wind's power is dependent upon the cube of the wind velocity. An average wind velocity is 7 m/s, for instance, derived from /67 wind velocities from 9 to 5, e.g., will give the figure of 343 for the cube of the average velocity, while $(9^3 + 5^3)/2$ gives the figure 474, a difference of 38%.

This mistake is equalized somewhat in actual conditions by the fact that the variations between 9 and 5 are small most of the time in actuality. Furthermore, the characteristics of the mill will also equalize the relation somewhat, especially at wind velocities above 10-12 m/s, because the mill's efficiency drops /68 sharply at wind velocities above 9 m/s (shown by curves 3 and 5 in Fig. 3a).

As is evident from the table, there were large differences in monthly production between estimated and produced energy values. The average difference during 10 months of production, however, is only 10%.

This can be explained by the nature of the wind and the location of the mill. As shown on the map in Fig. 7, the mill is built on a hill east of a bay on the west coast of Zealand. Winds from the west and the southwest come from the Smaaland Sea; these have a steady character, while winds from the NW, N, NE, E and SE come to the mill over land, and thus have an unsteady character.

As shown in Fig. 8, the last-mentioned wind directions were predominant in the months of January, February and May and give the large plus difference in the mill's production.

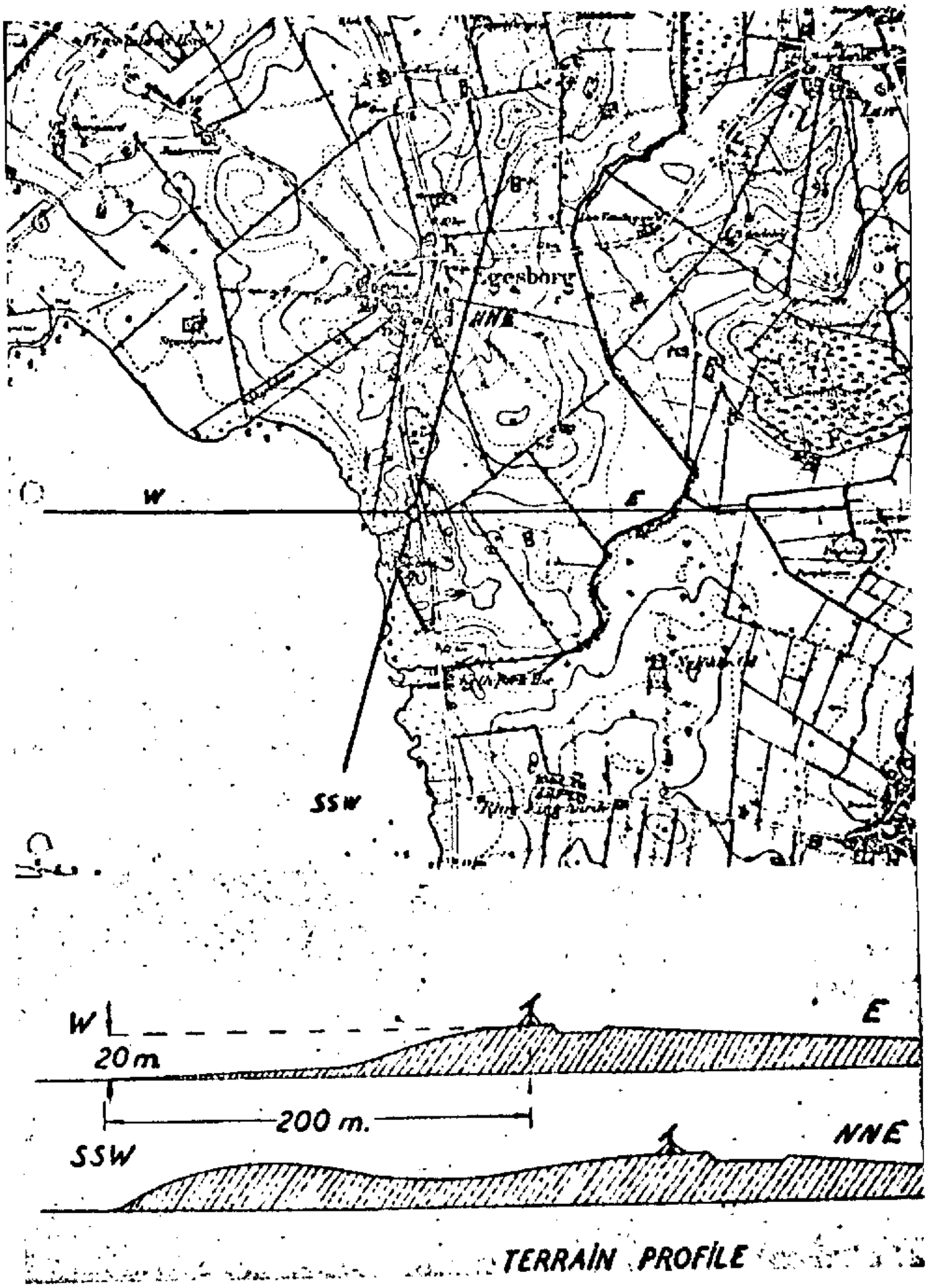



Fig. 7.

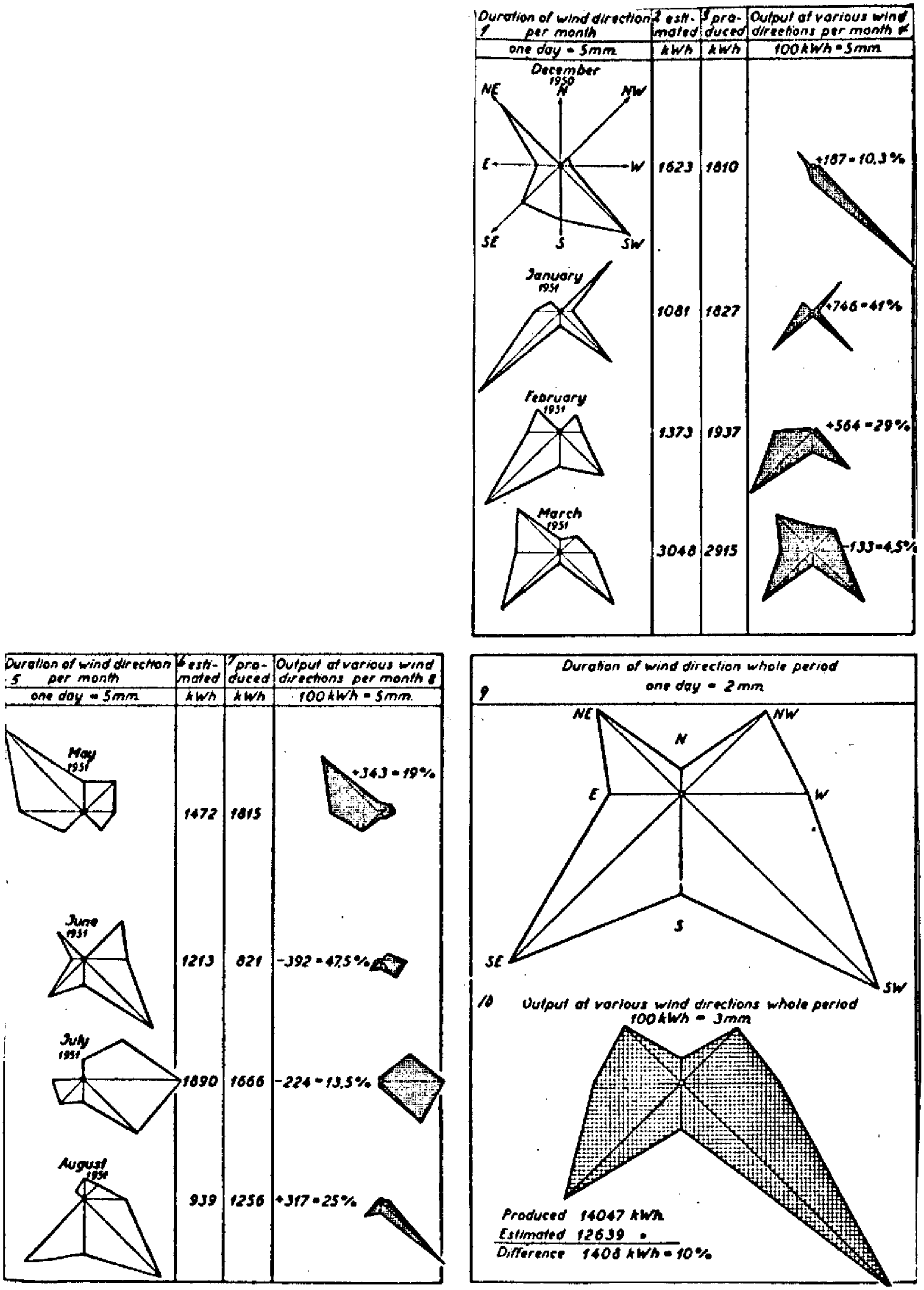

Duration of wind direction per month
one day = 5mm
estimated kWh
produced kWh
Output at various wind directions per month
100 kWh = 5mm
December 1950
NE
N
NW
E
W
SE
S
SW
1623
1810
+187 = 10,3 %
January 1951
1081
1827
+746 = 41 %
February 1951
1373
1937
+564 = 29 %
March 1951
3048
2915
-133 = 4,5 %
May 1951
1472
1815
+343 = 19 %
June 1951
1213
821
-392 = 47,5 %
July 1951
1890
1666
-224 = 13,5 %
August 1951
939
1256
+317 = 25 %
Duration of wind direction whole period
one day = 2 mm
Output at various wind directions whole period
100 kWh = 3mm
Produced 14047 kWh
Estimated 12639 "
Difference 1408 kWh = 10 %

Fig. 8.

In the months of June and July there were primarily weak west winds of a steady character, which give only small readings on the anemometer scale. Therefore, it is difficult to determine the average wind velocity correctly, and it must now be assumed that the minus difference appearing for these 2 months is primarily due to an overly optimistic estimate of the average wind velocity.

The system which aims at determining the energy obtainable from the wind by measuring the average wind velocity per time unit, and computing the energy obtainable by multiplying the wind velocity by the mill output, has thus been working in the given case with approximately 10% accuracy, but it also shows that when wind conditions are relatively unsteady, then considerably larger variations will arise, and that the mill under these conditions will be able to produce 30-40% more than the calculations indicate.

In the period from December 1950 to September 1951, daily production was recorded and indicated in Fig. 10. Out of 244 days there were 25 days when production was zero. From the diagram, it appears that wind power occurs in maximum and minimum periods, usually with a duration of a few days.

With the help of the meteorological observations which in most countries are now publicly available, the utilization of wind power can be organized in conjunction with other power sources in such a way that the operation can be appropriately organized.

The production for the period from 3/1/1950 to 3/1/1951, according to the anemometer readings, is estimated at 550 kWh per $m^2$ of wingspan area. If the 10% more than estimated which the mill produced in 10 months is added, an annual production of 616 kWn per $m^2$ of wingspan area is obtained.

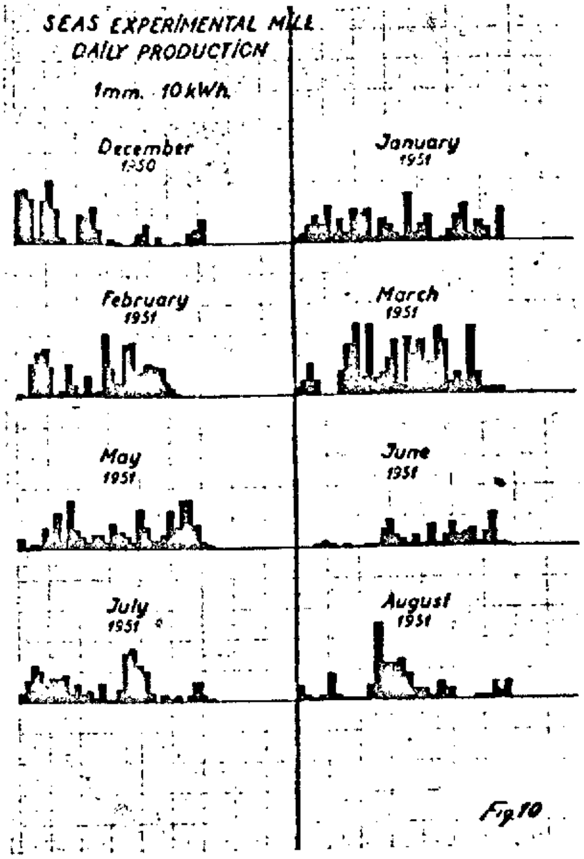



Fig. 10.

A standard windmill with a wing diameter of 24 m, corresponding to 450 $m^2$ of wingspan area, will be able to yield about 280,000 kWh under equal conditions.

A mill of this type will, however, come in contact with higher air layers and greater wind velocities, and both mill and generator will, judging from all conditions, have a greater efficiency than the experimental mill, and as a result a correspondingly greater annual production as well. The generator in the experimental mill is, as mentioned before, an ordinary 38 volt short-circuit motor, which under the given conditions has run at a voltage of 400-420 V.

Its magnetization current is therefore abnormally large and its efficiency less than a generator ten times larger, specially built to be suited to the given conditions, and there is also a possibility that the mill's efficiency can be gradually improved as more experience is gathered, not only as regards the construction of the wings, but also as regards the adjustment of the relationship between the characteristics of the mill and the generator.

It can therefore be established that the experimental mill has produced considerably more than expected and previously calculated; cf. my article in Elektroteknikeren, No. 20, of 22 October 1949, p. 631, where production was estimated at 200,000 kWh annually from a mill 24 m in diameter located on the west coast of Zealand, corresponding to 450 kWh annually per $m^2$ wingspan area. The production has thus been 33% larger in spite of the fact that last winter was abnormal from a meteorological point of view, in that there was an east wind and quite calm weather in December, January and February.

In the same connection we can mention that the largest annual production, which in accordance with the statistics is obtained from a modern wind power station with a 24-m wingspan in conjunction with a DC network, is 160,000 kWh, corresponding to 350 kWh annually per $m^2$ of wingspan area, and that the average of 5 similar mills' production is 212 kWh per $m^2$ per year.

Another condition has also arisen in the production of the experimental mill, namely the condition mentioned earlier that the average of a sharply varying wind velocity gives considerably larger production than the average of more regular wind.

In my earlier account, in the issue of Elektroteknikeren mentioned above, I did not take this possibility into account. The wind measurements which were made showed that inland on a hilltop an annual production of only 160,000 kWh could be obtained, as opposed to 200,000 kWh annually on the coast, when /69 the average velocity was made the basis of the computation, but since the wind inland is considerably more irregular than on the coast, it could appear that, in practice, the same annual production could be achieved on hilltops inland as on the coast.

The question will be of great importance for the whole wind power case, since it is a great advantage to have wind power stations located evenly distributed in the whole region of a supply network as close to the place of consumption as possible.

Regarding Point 5 in the Program of Objectives

If a mill is coupled to an asynchronous AC generator by a suitable gear, the mill's wingtip velocity will be limited to a certain rate of revolution with a variation of approximately 5% upward from zero to full load corresponding to the slip in the generator. The experimental mill has been in operation with various gear ratios, whereby it has been possible to determine its characteristics at different wingtip velocities.

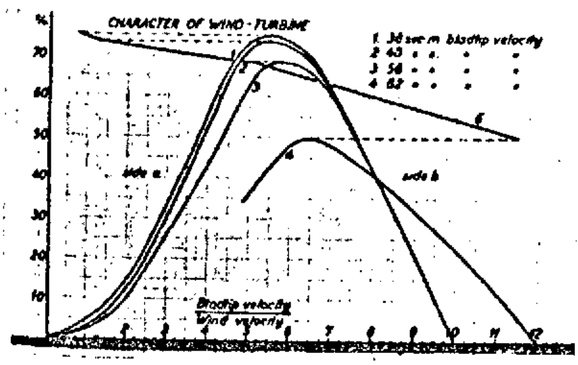



Fig. 11.

Curves 1--2--3 in Fig. 11 indicate the conditions found.

A noticeable drop in the mill's efficiency was ascertained with increasing wingtip velocity. Curve 4 was extrapolated from the power curve indicated for Smith-Putnam's experimental mills on Grandpa's Knob discussed in the book Power from the wind.

This mill ran at a wingtip velocity of 82 m/s.

Curve 5 indicates the maximum efficiency with increasing wingtip velocity.

It will be seen from this that increasing wingtip velocity causes a drop in efficiency.

From the shape of the curves, it is seen that the greatest efficiency was ascertained at a wingtip velocity of 38 m/s, when this is 5-6 times as great as the wind velocity. It is safe to assume that it would also be expedient to provide the mill with a generator which is capable of producing electricity at a variable rate of revolution. This has also been practiced where mills have produced DC current, in that there one can relatively easily establish a differential excitation of the magnetization, which causes the mill to run at an increasing rate of revolution at increasing wind velocity.

In the production of AC current the wingtip velocity in relation to the wind velocity can be varied in different ways. This was tested on SEAS' experimental mill by alternating in such a way that a six-pole generator was cut in during weak winds and a four-pole generator during strong winds. Part of the advantage gained by this alternation was lost due to the drop in efficiency with increasing wingtip velocity. Furthermore, it proves impossible to continually create the ideal conditions, both in regard to differentially exciting DC generators and alternating-pole AC generators.

The reason for this is that the mill, due to its inertia, cannot go up and down in rate of revolution rapidly enough according to the variation in wind velocity, especially when the wind is "land wind" and possesses a sharp variable character in contrast to "sea wind," which is less variable.

The experiments have shown that an approximately equal amount of power can be obtained from the mill when it is connected in an appropriate way to an asynchronous AC generator's rate of revolution. This must be chosen while taking the local wind conditions into account, and at SEAS' experimental mill it was found to be 38 m/s wingtip velocity. The efficiency is thus greatest at 6-9 m/s of wind, which are the most frequent winds in South Zealand. Where the wind velocity is more often greater than this, it would be practical to let the mill run at a somewhat greater velocity.

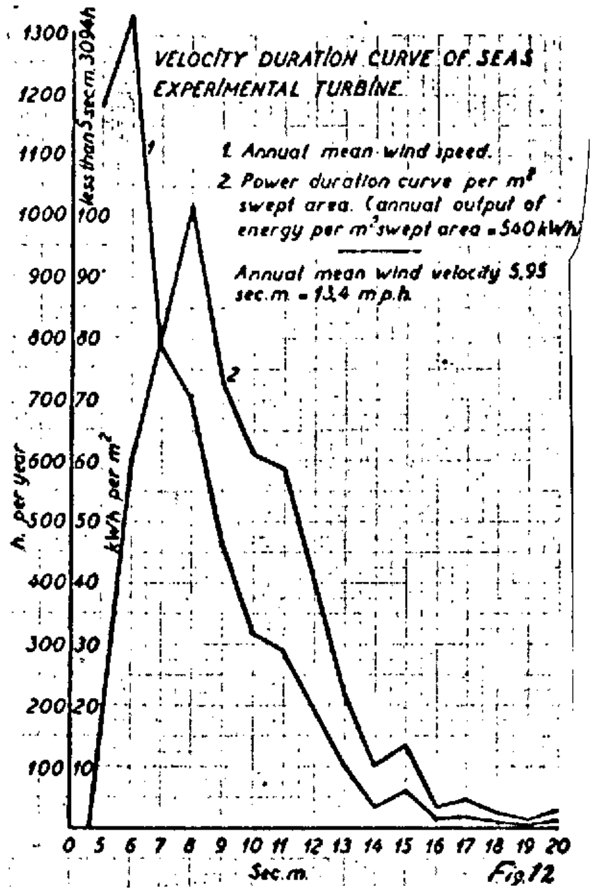



Fig. 12.

It has been shown that the experimental mill starts up safely at a wind velocity of 4 m/s. The amount of energy that can be produced at wind velocities below 6 m/s will be small, however, as shown by curve 2 in Fig. 12. Due to the smaller number of hours annually when the wind is above 13-14 m/s, the amount of energy produced at these wind velocities will likewise be of only minor importance. /70

According to the results obtained, therefore, it is not practical to pay for the necessary complex automation and increased costs for reinforcement of transmissions and generators in order to utilize wind velocities above 13-14 m/s with the greatest possible efficiency of the mill.

Mills of the old design are all equipped with reefing devices which serve to reduce the mill's output when the wind velocity reaches a certain magnitude, usually 10-12 m/s.

In the old Dutch mills, this occurred by stopping the mill and reducing the spread of canvas on the wings. In newer mills the regulation is usually provided with mechanical devices such as flap sails or turning mechanisms which turn the wings out of the wind, or brake flaps on the wings which are activated by the centrifugal force of the increased velocity of the wings.

It has been shown that the task of these devices on the experimental mill can be limited to starting and stopping it. This is accomplished by fastening the asynchronous generator to the mill's main axle, thus forcing the mill to run at a certain rate of revolution from the moment it is cut into the AC network at approximately 5 m/s wind velocity up to the highest occurring wind velocities.

The situation is that the mill, at about 5 to 7 m/s of wind, is working on the forward side (side a) of its efficiency curve (see Fig. 11).

As the wind gradually increases in velocity, the top of the curve is reached at 6-8 m/s of wind. If the wind velocity rises above this, the mill is working on side b. The efficiency drops, and in spite of increasing wind velocity, the generator will not yield more than a certain output, even if a hurricane is blowing.

In this way a mechanical output regulation of the wing is superfluous. It is essential for the generator's peak value to be more than the maximum power which is obtained by this method. If this is not the case, the slip will increase to a large value and the mill's rate of revolution will go up.

The generator in the experimental mill is provided with a star-delta changeover switch. It is advantageous to run with the generator in the star position, because the magnetization current will then be low. At a wind velocity of about 15 m/s, the output of the wind turbine exceeds the peak power value of the generator, and the experimental mill then increases in velocity until the safety mechanism is activated. In order to avoid this, the generator must be changed over to a delta connection. Its peak value is thus situated considerably higher, and it is capable of keeping the mill in phase with the network frequency under any wind condition.

In the final design of a wind power station it is important that the asynchronous generator be built specially for the job, primarily because the generator runs at the highest voltage at full load, while as a turbine it will run at the lowest voltage at full load. Moreover, it is advisable to design it so that it has the greatest possible slip at full load without coming too close to its peak value; thus the mill's characteristic curve can be flattened out somewhat on the back side (side a, Fig. 11).

As it is undesirable to load the network with the generator's magnetization current, this can be compensated for by the insertion of a suitable capacitor. This arrangement will, in any case, be less expensive, simpler and more reliable than using a synchronous generator with the accompanying magnetization machine. Furthermore, the use of an asynchronous generator means that there are no problems with regard to voltage regulation, because the generator does not change voltage to an appreciable degree between zero and full load. In networks to which wind power stations are connected in this manner, the voltage can be regulated with the equipment at hand, and the generator can be automatically cut into the network in the most simple manner without using synchronization apparatus. The brake flaps mounted on the wings proved large enough, before the bracing wings were added, to prevent the mill from exceeding its normal rate of revolution in a gale. After the bracing wings were added, it was shown that the mill's rate of revolution can run up with the brake flaps out when the generator is cut out of the network, but in connection with the mechanical brake on the main axle the stopping mechanism can function safely in a gale. The surface area of the brake flaps is 2300 $cm^2$, corresponding to 0.575% of the wingspan area.

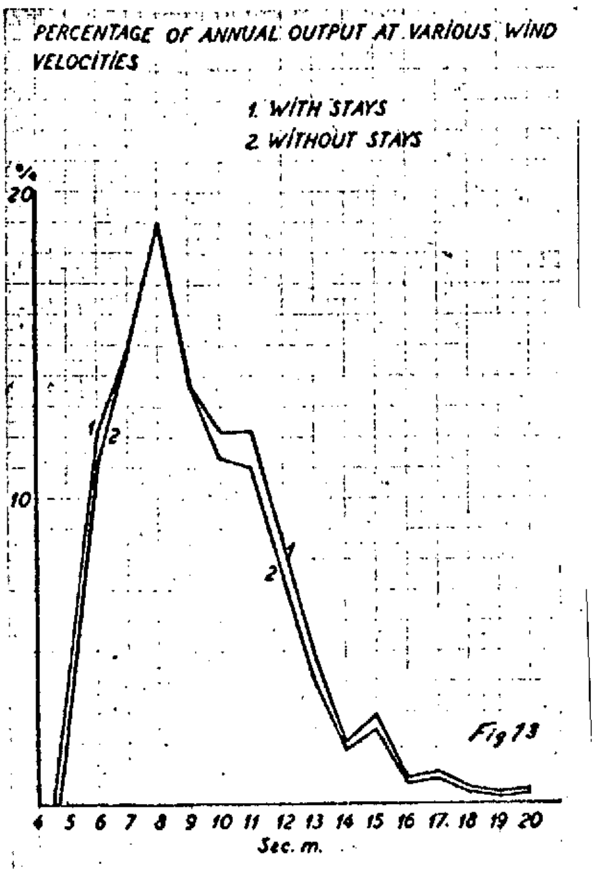



Fig. 13.

The brake flaps are con- /71
nected, by means of a steel wire, levers and a tension rod through the mill's main axle, to a piston in a compressed-air cylinder, in which the piston is held in working position by approximately 4 atmospheres of air pressure. It is possible to regulate the air pressure in the cylinder through a valve system in combination with a power relay and thereby counteract the centrifugal force in the flaps, so that they can assume any position from flight position with the wings up to 90° perpendicular to them.

The mill's output could be regulated by this means if necessary. Since this is not the case, however, and since the flaps are only intended to stop the mill when there is no voltage in the network, or whenever else it is required, the regulating valve and power relay of the wind power station can be dispensed with.

Various cut-in methods have been tried. In the beginning, the cut-in was carried out by a wind pressure relay which cut in the generator at 5 m/s of wind, and cut it out when the wind velocity fell below about 4.5 m/s. This arrangement was chosen because it was assumed that the mill would not be capable of starting by itself at the right time in 5 m/s of wind. Indeed, it could not at the start, when the transmission between the generator and the main axle consisted of a chain drive to a secondary axle and V-belt drive from this to the generator.

The V-belt was replaced by a chain drive, and now the friction in the transmission was reduced so much that the mill could start safely in 5 m/s of wind.

The wind pressure relay resulted in a good deal of unnecessary switching, and in addition, it also cut in either when the mill was not up to full velocity or when the velocity was too great. The result was mechanical pulsations in the transmission and electrical pulsations in the network.

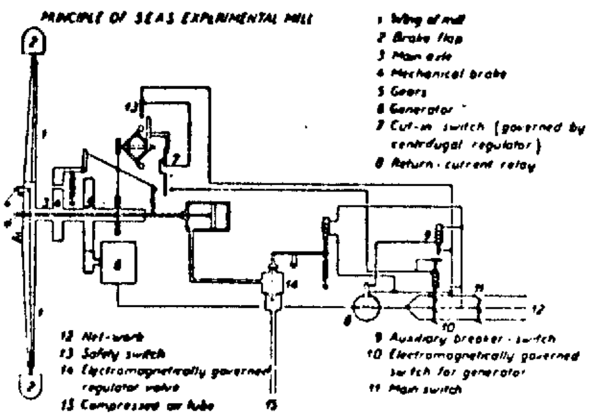



Fig. 14

The cut-in system was therefore altered so that a centrifugal relay driven by the mill's main axle cut in the generator during a synchronous rate of revolution, and a return current relay in the generator circuit cut it out when the wind dropped so much that there was return current to the generator. Figure 14 shows the principle of the mill.

The cut-in relay is an ordinary motor protection relay adapted for push-button control. The centrifugal relay replaces the start switch, and the return current relay the stop switch. However, it was necessary to insert an intermediate relay so that the return current relay makes contact with an intermediate relay which acts as a stop switch. It turned out that when the return current relay was supposed to cut off the stop switch, it took place so slowly that the resulting spark caused radio static.

A third cut-in system has also been tested. It consisted of a small asynchronous motor whose armature was directly coupled to the generator's main axle, while the stator was in a rotatable suspension. The stator on the relay motor was wound so that it could tolerate being constantly connected when the rotor was at rest. The torque in the stator was thereby capable of holding a stop switch open when the generator was still at rest, or when it received return current from the network because of too little wind. When there was so much wind that the generator exceeded the synchronous rate of revolution, the rotating field changed direction in the relay motor's movable stator, which then closed the start switch.

Since in the stop position the relay motor uses current from the network and also appears to be difficult to be made to work with the required accuracy due to the relatively large weight in the stator, the cut-in system was changed back to the centrifugal regulator as start switch and the return current relay as stop switch. This is the system which has proved to function best, and it cuts the generator in and out with great accuracy in such a way that cut-in and cut-out occur without noticeable pulsations in transmission parts or network. /72

## Effect of the Wind on Wings and Tower

Calculation, design and construction of a wind power station in such a way that the requisite resistance to breakage is obtained without the use of superfluous quantities of materials requires detailed knowledge of the forces which the construction parts are exposed to.

The experimental mill is, as shown in Fig. 1 in the first report, constructed upon a lattice tower 13 m high. On this at a height of 8 m a ring is fastened in which the lattice tower can be turned and to which the guywires are fastened. The lattice tower's journal is located on a lever whose free end rests on a spring. When the wings revolve in the wind, it will be retarded, and an axial pressure arises, as well as a pressure resting upon the lever which has a definite relation to the axial pressure. The spring will yield, and a self-recording pressure gauge connected to the lever will register. The pressure gauge is adjusted by a dynamometer tension in the mill's axle in such a way that intermediate calculation is avoided.

The pressure gauge is arranged in such a way that pressure originating from low wind velocities does not register, whereby greater accuracy of measurement is achieved at the wind velocities which most affect the mill.

The readings from the pressure gauge are shown in Fig. 15 and have the same character as the readings from the kW-meter. The effect is determined by relating the highest readings on the pressure gauge to the highest readings on the anemometer during the same period.

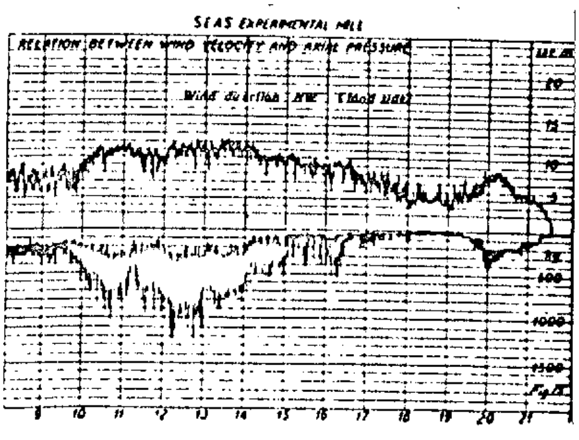


Fig. 15.

The points marked with open circles on the coordinate system in Fig. 16 are caused by land wind, while points marked with dots are caused by sea wind. From this it will be seen that the irregular land wind affects the mill more than the regular sea winds. For the irregular land wind the system's fundamental vibrations have increased the readings a bit, and it must be assumed that the highest readings for sea wind are also to some degree affected by systemic vibrations. During the time the mill has been in operation, there have been no wind velocities in

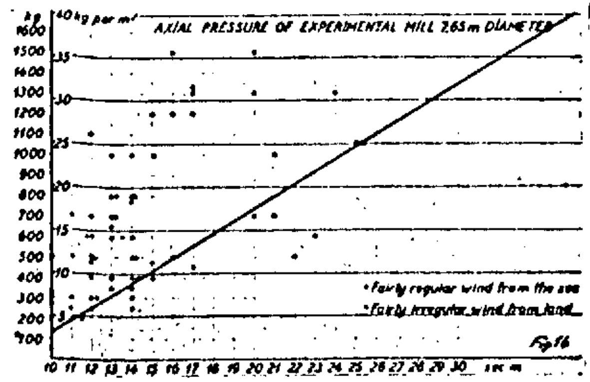



Fig. 16.

excess of 25 m/s. An average curve drawn through the points for sea wind shows that up to about 50 kg of axial pressure per $m^2$ wingspan area must be expected. Furthermore, the character of the axial effect varies sharply from + minimum to + maximum (see Fig. 15).

The cause of the variable axial effect is that the wings do not revolve in homogeneous wind. This is most noticeable in the vertical direction, because the wind velocity increases in relation to the height (see Fig. 24). The pressure on the wings will therefore climb from their bottom to their top position, thereby causing a regularly variable effect upon the wings and tower.

In the design of these parts these conditions must be taken into consideration, and the possibility of the various systems' fundamental vibrations coinciding with the rate of revolution of the wings must be avoided, or of interference arising between the rate of revolution and the fundamental vibrations.

It must be assumed that effects upon the wings caused by axial pressure will be distributed along the wings from the center according to a scale which correspoinds to the relation of each point on the wing to its periphery. The relationship is shown in Fig. 17, where line 1 indicates the effect on a wind in kg per length unit, while line 2 indicates kg·cm at the base of the wing.

If one calculates the dimensions of a girder in the wing which could tolerate the given effects, it is proved to cause great difficulties to design the wing with an appropriate

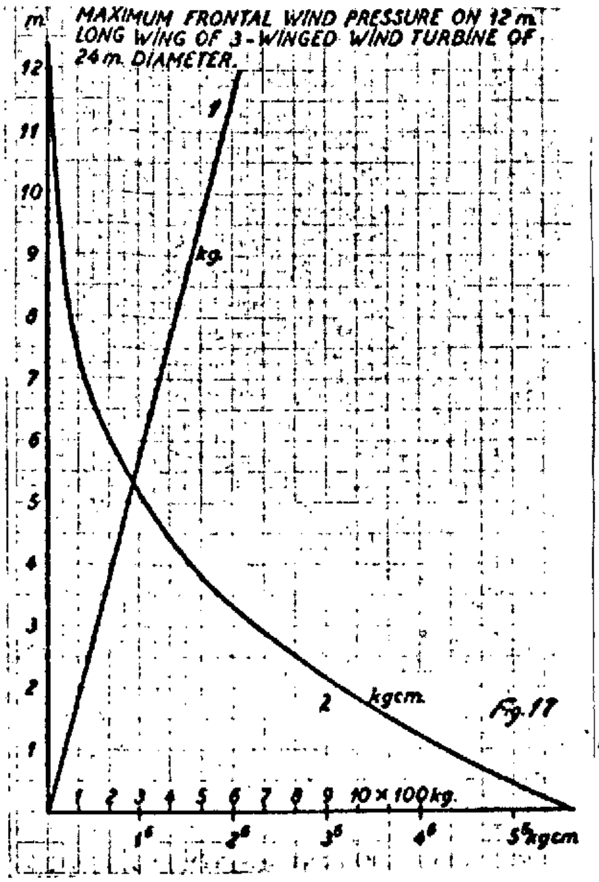



Fig. 17

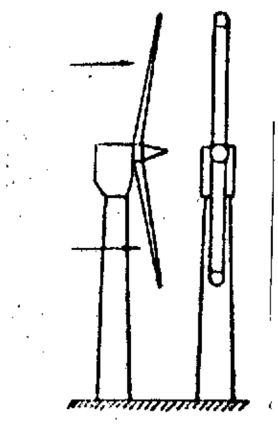


Fig. 18.

streamlined profile so that it obtains the required strength, unless bracing devices outside the wing profile are used. By giving the wing the swept-back form shown in Fig. 18, the wind pressure can be relieved to some degree by the centrifugal force in the wing.

In order to solve the problem in this manner, the wings must have a relatively large backward sweep, and they must run with a relatively high wingtip velocity. Both are not feasible because of other considerations. At the wind velocity of 38 m/s found to be most favorable at the experimental mill, centrifugal force cannot solve the problem. The experimental mill's wings had to be rebuilt as a result and were provided with bracing as shown in Figs. 19 and 20.

Besides the axial pressure, the wings are affected by gravity and torque. These forces, however, lie in the lateral direction of the wings, displaced 90° from the axial pressure.

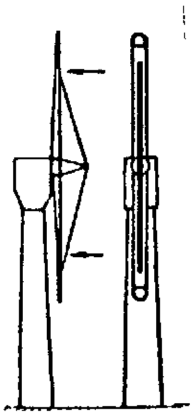


Fig. 19.

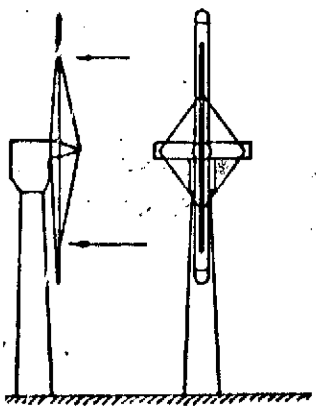


Fig. 20.

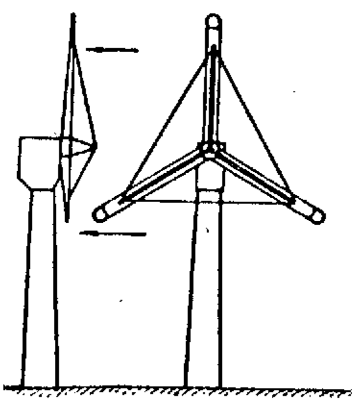


Fig. 21.

A three-winged turbine 24 m in diameter which develops maximum 120 kW = = approximately 200 HK will give each /73 wing an effect which will be converted to the wingtip at 38 m/s wingtip velocity:

$$kg = \frac{200 \times 75}{3 \times 38} = 131 \text{ kg}$$

and a torque at the base of the wing of 131 x 1200 = 157,200 kg·cm.

If the weight of the above-mentioned wings is, for instance, 1000 kg, and if the center of gravity is located in the midpoint of the wing's length, the effect is obtained:

600 x 1000 = 600,000 kg·cm

at the base of the wing.

While the maximum axial wind effects only occur quite seldom, and as effects which arise varying from plus minimum to plus maximum, the effects caused by gravity occur as a plus maximum value to a minus maximum value with each revolution of the wing. The effect will proceed according to the sine curve shown in Fig. 22. In weak wind, the plus and minus effects will be of equal magnitude, in practice, while the

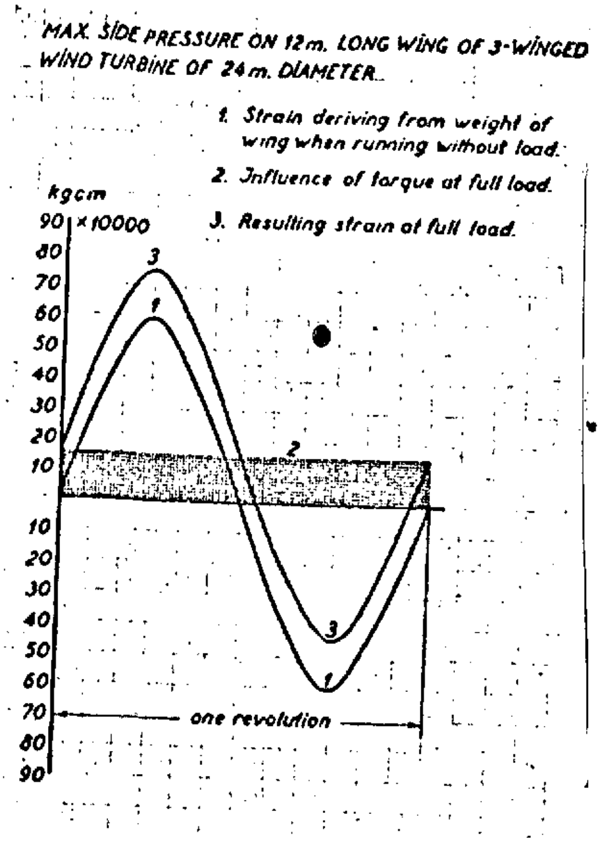



Fig. 22.

effects in strong wind will be altered by the torque to a relatively larger value during the wing's period of downward motion and to a relatively smaller value during the wing's period of upward motion (see curve 3 in Fig. 22).

Overloading of the wings due to wind pressure in a gale will generally appear as a deformation (bending) of the structural parts, while overloading caused by gravity appears as fatigue breakage, and since the latter effects are most critical in weak wind without torque, then breakage of the wings caused by gravity will primarily occur in weak wind.

The first set of wings on the experimental mill were built with the expectation that the centrifugal force would equalize the wind pressure. They were designed to run at about 60 m/s wingtip velocity in strong wind, but since it appeared expedient to let the mill run at only 38 m/s, the wings were too greatly loaded in strong wind. During the designing of the wings, it was also not foreseen that the wind pressure would be so large, as later proved to be the case by direct measurement on the wind pressure gauge.

After barely 3 months of operation, there was breakage in the wings, in that the outermost end cracked. The girder in the wings was constructed of steel pipe so that the inner section was 93 mm in diameter, while the outer section was only 50 mm in diameter. The break occurred where the two pipes were welded together. A calculation with the measured wind pressure as a basis showed that the load a few days before the break occurred had been close to the yield point of the material.

The break occurred at only 5 m/s of wind, and the break point showed that the defect could be blamed on fatigue in the material.

The wings were thereafter constructed in such a way that the 93-mm steel pipe went all the way out to the wing brake flaps. Furthermore, stays were attached to the wings to brace them against the wind pressure, as shown in Fig. 19. /74

The effect on the material was thereafter not above 800 kg per $cm^2$ at any place on the wings.

After being rebuilt, the mill ran for 4 1/2 months. It had been equipped with a vibration breaker switch which could stop the mill when excessive vibrations arose in the tower. On 1 April 1951, the mill stopped because the vibration breaker switch had functioned.

It turned out that one of the wings was bent about half a meter in the direction of revolution, and an investigation showed a crack in one wing's girder at the base. The crack clearly showed that it was again a case of fatigue breakage, and the break had again occurred in weak wind. In the first period, the mill had run about 10 million revolutions, and in the second period, about 18 million. A calculation showed that the first place of breakage had been subjected to 570 kg per $cm^2$ plus and minus effect for each revolution. During the second period, the place of breakage had been subjected to 550 kg per

$cm^2$ originating from the same effects. In May the wings were equipped with lateral stays supported by two small bracing wings as shown in Fig. 20. By this means, the effects caused by gravity were reduced to about 200 $kg/cm^2$.

The stays consist of flat bars which are formed so that they have a streamlined profile. They do not cause sound phenomena and have not reduced the mill's efficiency noticeably. The bracing wings are also streamlined and are provided with suitable bevels and have, as mentioned previously, increased the mill's output in weak and strong wind, whereas there is no noticeable increase in efficiency at 6-9 m/s of wind, where the mill previously enjoyed its greatest efficiency.

As a result of the measurements made and the experience gained, the conclusion must be that effects caused by wind pressure should not exceed 800 $kg/cm^2$ in any part of the wings or tower, and that effects caused by gravity in the wings should not exceed 200-300 $kg/cm^2$. This is valid when ordinary types of steel are used; in using special steel or other material, its special properties must be taken into account.

Furthermore, it appears that a design of mill wings which are to have relatively the same output as the experimental mill can only be constructed with the aid of bracing devices, in practice, and since bracing in the lateral direction is necessary, for this reason it would be expedient to build the mills with at least three wings, as shown in Fig. 21.

Up until 30-40 years ago, when windmills had not yet been put out of action by diesel and electric motors, the builders of mills were concerned with the choice between wood and steel as construction material for mill wings.

There had been centuries of experience with wooden wings, but they had the characteristic that their lifetime was only 12-15 years, depending on the quality of the wood. One had begun building wings of steel, but experienced mill builders criticized this material, because they were afraid that fatigue phenomena in steel structures would be manifested. They therefore preferred the old, thoroughly tested wooden structures. They knew that if steel structures were to be used, then it would be necessary to use bracing stays and struts; then they were afraid that these would work loose, and the breakage of a single stay could destroy a whole wing system.

Experience has shown in the meantime that the mills which were built then as braced steel structures have held up quite well. There are quite a few of these mills which have been in constant operation since then. Figure 23 shows such a mill which has been in operation for approximately 45 years.

## Regarding Point 5, the Height of the Supporting Tower

When the wind blows over the surface of the earth, frictional resistance arises between the air and the earth which reduces the velocity of the lowest layer of air.

The wind velocity will therefore increase in relation to the height above the surface of the earth.

An irregular, built-up and wooded region will suppress the motion of the lowest layer of air more than a flat, uninhabited and treeless region, and it is self-evident that along the coast there will be less restraint of the winds which come from the sea than of those which come from the land side.

The wind's increasing velocity in relation to height will therefore generally also vary with the wind direction.

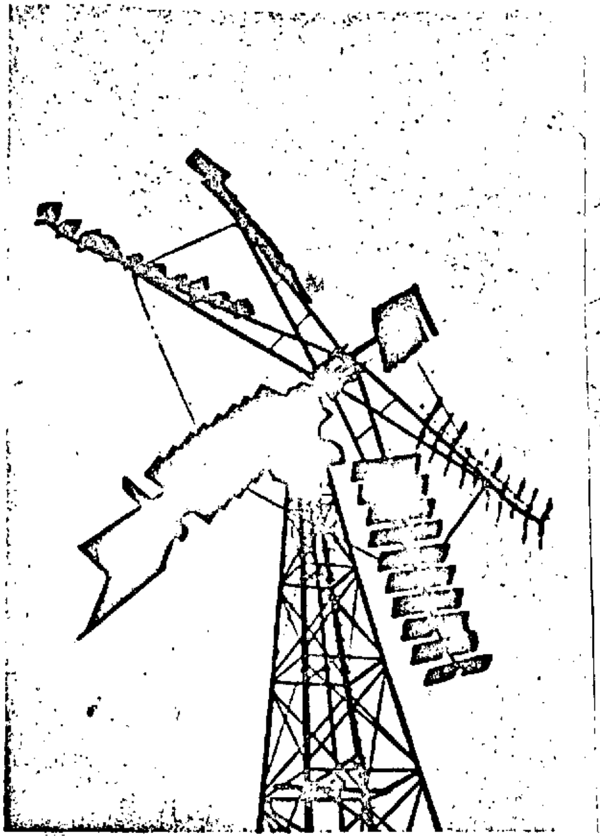


Fig. 23.

Simultaneous wind velocity measurements have been made at various heights to determine to what degree the wind increases in velocity in relation to height. Curves 2 and 3 in Fig. 24 indicate measurements taken by SEAS at the Geodetic Institute's measuring towers located in Terslev on hilly, wooded terrain and in the vicinity of Krummerup, where the area has a flatter character.

Curve 1 was determined according to an empirical formula provided by the Meteorological Institute, which indicates roughly the variation in wind velocity at the heights which are relevant in the construction of wind power stations.

In the following calculations, this curve is taken as the basis, and it follows that the calculations are thus approximations, and that the actual conditions are likely to change from place to place.

Since the wind's power varies with the cube of its velocity, it is obvious that a relatively modest increase in wind velocity will cause a quite considerable increase in the amount of energy. In Fig. 25, curve 1 shows the percent increase in wind energy on the basis of wind velocity measurements made at SEAS' experimental mill and computed according to the Meteorological Institute's formula, where

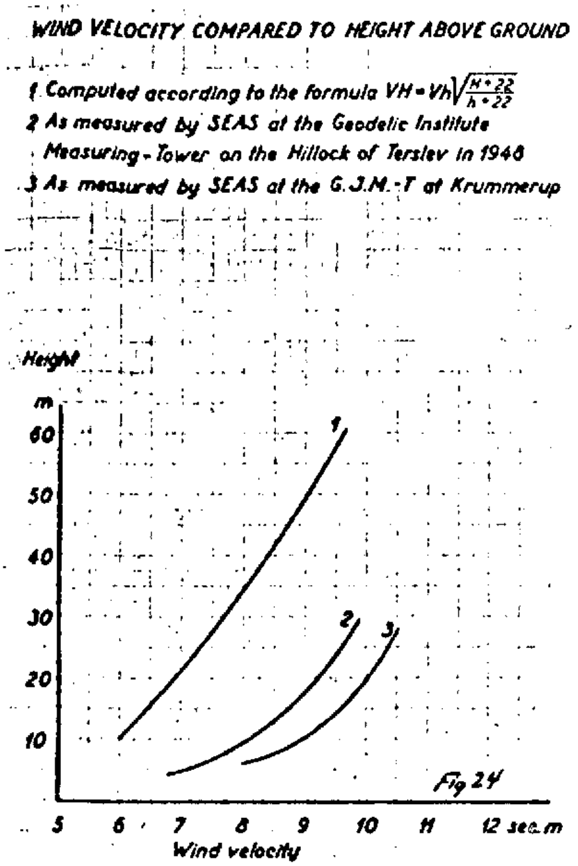



Fig. 24.

$$VH = Vh\sqrt{\frac{H + 22}{h + 22}}$$

where VH is the velocity at a great height and Vh the velocity at a lesser height.

Due to the experimental mill's characteristics, the increase in energy cannot be utilized fully, but the amount of energy which can be utilized by a wind power station adjusted like the experimental mill is shown by curve 2.

It will be seen from this that a wind power station with a tower about 45 m high will be capable of producing 100% more energy than if it is equipped with a tower 20 m high.

It would thus be more profitable to build wind power stations with relatively high towers. In designing these, one ought therefore to choose the form which fulfills this purpose with the least expense.

If the support tower is braced with stays, it will probably be less expensive to construct than a rigidly constructed tower, which up to now has been the form used most often.

Figure 26 shows a proposed design for a wind power station of 100 kW with a wing diameter of 24 m. The tower is 40 m high and braced with stays. The design is actually the old stub mill

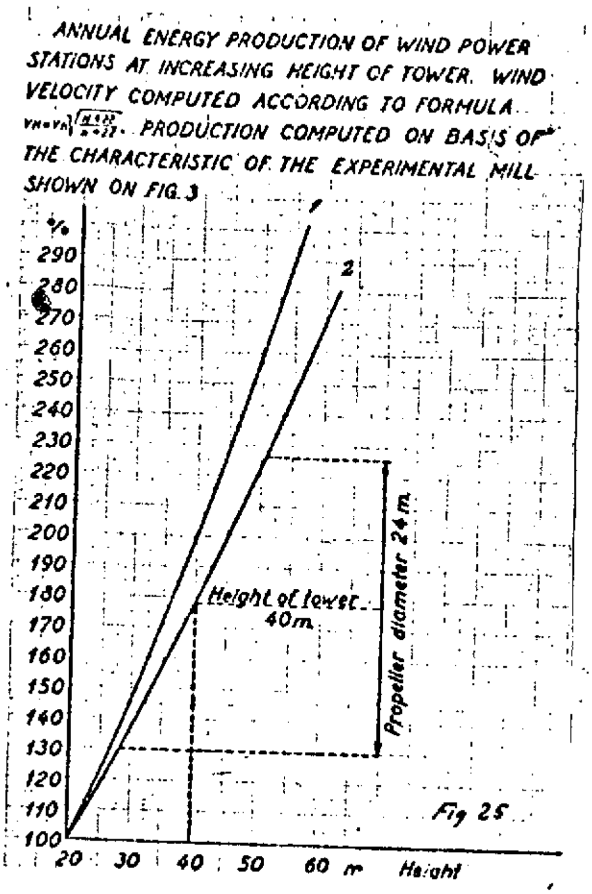



Fig. 25.

system, in which the wings are attached to a house (cabin), which is suspended so that it can rotate on the uppermost pointed part of the tower. In the cabin the generator is mounted along with the transmission machinery between it and the mill's main axle.

Since the mechanical power does not need to be transmitted down through the tower, the stub mill system is preferable to the Dutch mill system because a more solid connection between the tower and the rotatable part of the installation is achieved.

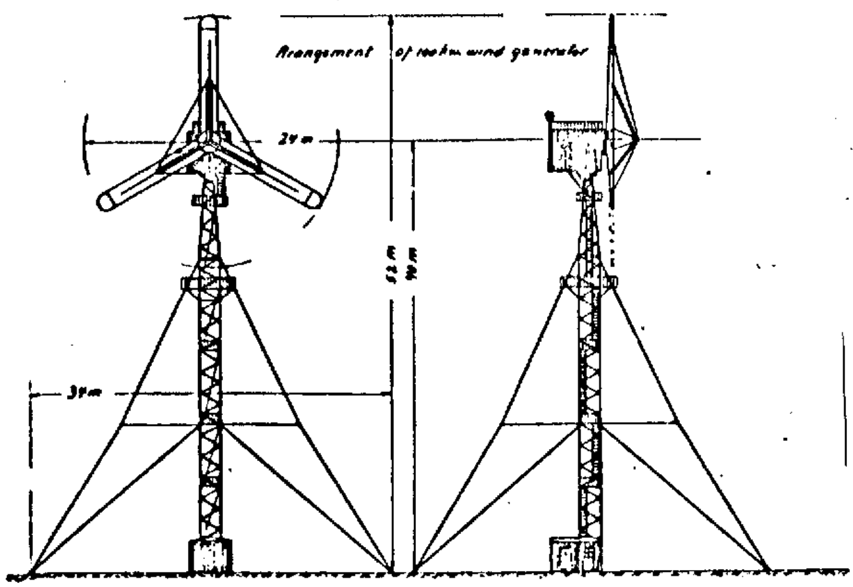



Fig. 26.

When this section must contain the main axle, transmission and generator as well as the mechanical brake and the mechanism necessary for the regulation of the installation, the cabin will be of the size indicated.

Out of regard for the operating personnel, it will also be a great advantage if the cabin is closed and has enough room so that they can work in it comfortably.

On the basis of the production results obtained with the experimental mill, and on the basis of the estimated increase in wind velocity in relation to height, such a station would be capable of producing about 400,000 kWh annually when it is favorably located with regard to wind conditions.

It is possible that it would be profitable to construct large rotatable towers on which several sets of wings can be mounted, but this should probably wait until more experience has been gathered with stations that only have one set of wings on a tower.

## Construction of Wind Power Stations

The distinctive fact about wind power stations is that they cannot be built to advantage in relatively large units, as is the case with heat power stations.

The energy in coal and solid fuel cannot be extracted without the occurrence of a chemical process in the form of combustion, whereby the energy is converted to heat, which then must be again converted to energy of motion before it becomes electricity.

For this to occur in an economical fashion, relatively large and complex installations and machines are required, with their accompanying transport installations, harbor installations and expensive distribution networks to the consumer. They are generally dispersed over a wide area and most often use energy in small units.

Wind power stations, in comparison to steam power stations, are much simpler and obtain energy of motion directly from the power source. They run fully automatically, and the tending of wind power stations is limited to periodic maintenance.

In a large supply region there will also be a large and virtually ubiquitous network to which a large number of wind power stations can be connected without technical difficulties, as close to the place of consumption as possible and at expedient locations which offer good wind conditions. The economic and technical conditions will be decisive for the size of the individual units to be constructed, and the amount of energy to be /76
gained will be decisive for the number of units to be constructed.

Wind power stations can be constructed according to various systems.

The decisive factor for whichever system will be most advantageous to use under the given conditions is the amount of energy the system can produce in relation to the costs of construction, regardless of the efficiency one obtains from the energy of the wind, because there is ample room in the wind for the necessary number of wind power stations.

Meanwhile, it is highly probable that the windmills which run with the greatest efficiency are also the ones which will require the least material, and as a result they will probably also be the least expensive to build.

The oldest windmills were built according to the stub mill system. They consisted of a house which supported the mill's wings. In the house, the working machines were mounted, which were driven by the wings.

The house, along with the entire mechanical apparatus, was mounted so that it could rotate upon a "stub" placed in the ground. At a later date, the Dutch windmill appeared. It was used in Holland primarily for water pumping, and since water pumps, because of their nature, could not easily be installed in a rotating house, the wings were mounted upon a rotating "hat" on top of a fixed building, and conical gears on the wing axle transmitted the power to a vertical axle in the fixed middle portion of the building.

It was the Dutch type of windmill which finally became predominant and which served as the prototype for the more modern wind turbines which were designed to power fixed machines located in or near the mill building.

Thus, there are several known systems of wind power stations to choose among when wind electricity stations are to be built, but there is also some talk of completely new systems, for example, the system proposed by Prof. Andreau of Paris, which is gearless.

The arrangement of SEAS' experimental mill, however, is based on the old principle in which there is a mechanical transmission between the mill's main axle and the working machine, in this case, an asynchronous AC generator. If this system is to be used, the following questions must be answered:

1) the size of the wingspan, gears and generator

2) the height of the supporting tower

3) the method of mounting the wings, transmission and generator on the support tower.

4) whether there should be one or more wing systems on the same tower

5) fixed or rotating support tower.

In regard to point 1, the conditions are such that a wing system must run at a peripheric velocity which is in a definite proportion to the average velocity of the wind at the point of mounting.

By increasing the diameter, the rate of revolution of the main axle decreases as a result. Power increases with the square of the wing diameter, and the same is the case with bearing pressure and gear pressure, provided the diameter of the gears is increased in proportion to the wing diameter. At a wing diameter of about 25 m, the limit will be reached of the size of the transmission parts which are normally manufactured and with which there have been satisfactory long-term results.

Dimensions of transmission parts over normal size will in all cases be quite heavy and expensive and will require long-term testing and expensive examinations before they can be recommended as the basis of wind power stations.

The conditions in the construction of wind power stations can be compared with the conditions which manifest themselves in the construction of internal combustion engines. In this area, there is also an economic limit to the size of the individual unit. Therefore, multiple cylinder diesel engines are built.

The world's largest diesel engine center was built in Texas. It is 120,000 kW. Each engine is 1000 kW and is constructed as a radial engine with 11 cylinders. Here, the individual unit is, therefore, barely 100 kW. The advantages of this type of construction are, among others, the fact that expansion, maintenance and repair can take place as an evenly flowing task which does not cause noticeable jumps in the power available. Moreover, this method of construction proved to be the most economical under the given conditions.

The largest wind power station known today is the Smith-Putnam station on Grandpa's Knob, in the USA. It had a wingspan of 53 m and was equipped with two wings on a tower 45 m high. The generator here was a synchronous AC generator, and the mill ran at a wingtip velocity of about 80 m/s. It developed 1500 kW at 16 m/s of wind, and approximately 700 kW at 12 m/s. The station was a disappointment, however. It was soon evident that the strong winds were almost as infrequent on Grandpa's Knob as on /77
Zealand, and with the large peripheric velocity, the station was not capable of producing current until about 9 m/s of wind, and then with poor efficiency.

If the mill had been arranged so that it only ran at half the speed, it could have produced more than twice the amount of energy, and it would then have been unnecessary to design gears and generator for more than about 600 kW. The station was actually the size of a 600-kW station, according to the adjustment which is expedient under our wind conditions, and would also have been in America. The whole station weighed 320 tons, i.e., 530 kg/kW.

A wind power station of about 100 kW on a tower 40 m high will weigh approximately 30 tons, corresponding to about 300 kg/kW. It would thus without doubt be relatively much more expensive to build 600-kW wind power stations than the same at 100 kW.

Technical difficulties also appeared in keeping the Smith-Putnam station in operation.

First one of the main bearings broke, and when it had been changed, a short time later one wing cracked due to fatigue breakage caused by gravity in the wing. The station was then dismantled.

In America, there is more interest now in smaller wind power stations, of which many are being built.

In Russia, projects have been worked out for large wind power stations with wings up to 60 m in diameter. As far as we know, a type has been decided upon with a maximum diameter of 30 m, however. This type is used for electrification of collective farms in Russia.

Without having investigated the matter exhaustively, it seems that wind power stations of about 100 kW with a wingspan approximately 24 m in diameter are the most economical type. Such a station is approximately equal in size to the old Dutch windmills, whose size was determined by centuries of experience.

Many years of experience have been gathered in building the machinery of modern construction necessary for such a station for other mechanical purposes. It must therefore be assumed that it will also be possible to build the necessary machine parts for wind power stations of this size with no difficulty so that they will be stable and durable for many years.

## The Economics of Wind Power Stations

If wind power stations are to have any economic importance, obviously many stations must be built. In Denmark 30 to 40 years ago, there were between 2500 and 3000 Dutch windmills designed for milling grain. They had a wingspan of 18-24 m and almost all of them were built according to the same well-known model.

Moreover, it is estimated that there were at least 30,000 smaller wind motors built on large and small farms and small industrial and craft establishments.

If one imagines the old Dutch grain mills replaced by an equal number of wind power stations of modern design, they would be capable of producing half of Denmark's present electrical consumption, and they would replace an annual coal import of about 600,000 tons, corresponding to a currency demand of 60-100 million kroner at the present prices. Furthermore, the country's electrical supply would become less dependent upon the international coal situation.

It does not seem to be an insurmountable task to replace, in the next 10 years, for example, the old windmills with modern wind power stations. This could happen with the contribution of modern technology and working methods.

It will probably be expedient to organize a national institution which can build the wind power stations or have them built with the help of private enterprise.

In addition, this institution probably ought to run and maintain the wind power stations as well, and sell the electricity produced to existing electrical supply companies.

Whether such an institution is to be started as a corporation or cooperative society with the supply companies as the main stockholders or cooperative members probably does not matter; only it must not serve interests other than that of supplying wind electricity in the least expensive manner to the supply companies. /78

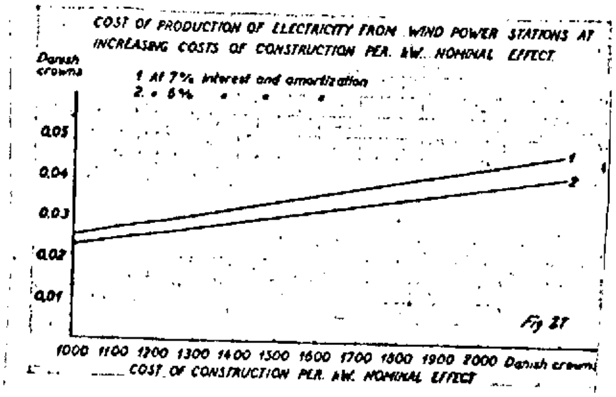
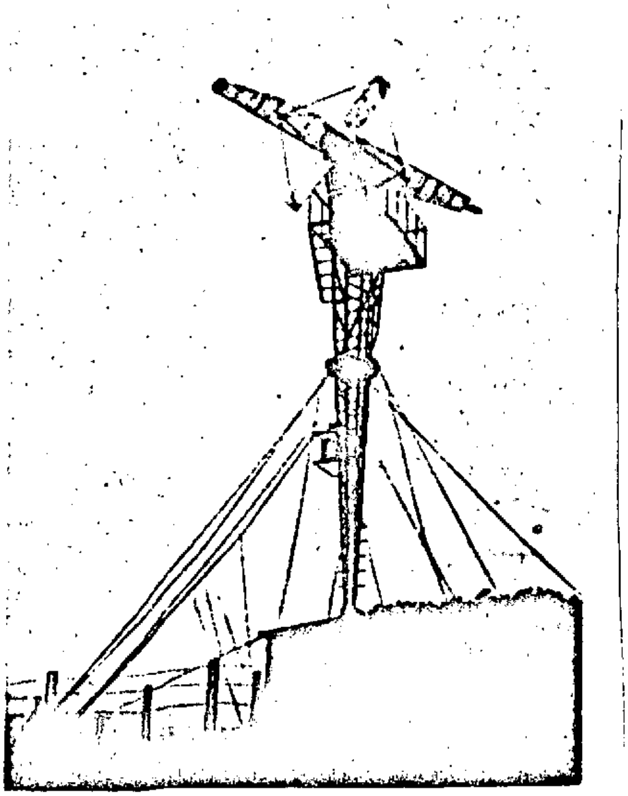



Fig. 27.



SEAS' experimental mill.

The supply companies ought to pay a price for the electricity which secures the usual interest and amortization of the installation capital. The question is thus what wind electricity will cost.

Here the installation costs play the major role, and with the present varying prices of materials and wages, it is obviously difficult to say anything definite about it.

Two years ago, the British expected to be able to build wind power stations for 800-1000 kr/kW, but these prices will hardly be applicable now.

Tending and maintenance of wind power stations will obviously also have an influence on the price of production. It will therefore be of interest to sketch how this side of the matter can be arranged.

Wind power stations of about 100 kW can be erected approximately 500 m apart without interfering with each other, but since winds traveling south and north are quite rare, there is no reason not to place them in a row from north to south with approximately 200 m between them, where wind conditions permit.

Since the operation of wind power stations which produce alternating current is fully automatic, maintenance is limited to lubrication and inspection about two times per month. This must be carried out by specialists who are used to working at great heights.

Out of regard for the nature of the work, it is also necessary that it be done by two men working together, and that they have a tool truck available. If this is the case, two men can be expected to take care of 25 stations when they are located within an area whose outermost points are not more than 40 km apart.

In addition, it will be necessary for there to be a local supervisor, who will have no other task than to report when a station has stopped or when other abnormal conditions appear.

Maintenance and replacement of larger parts of the stations ought to be undertaken by a more centralized work team who have access to cranes and similar special tools.

A work team will probably be able to take care of this type of necessary replacement and repair in an area with 200-300 stations.

The main cost in the production of wind electricity will be interest and amortization of the installation costs.

The price of wind electricity will thus be primarily dependent upon how the financing of the stations takes place, and how long it will take to amortize the installation sum, and here the lifetime of the stations must be taken into account.

The experience from the stations which were built 40 to 50 years ago shows that wind turbines which were built with steel wings have a relatively great durability. An amortization period of 25-30 years therefore seems justified, when an appropriate maintenance cost is included.

In the construction of wind power stations on a large scale, two areas of social importance are touched upon. First of all, that the country's power supply is based on domestic power sources to as great a degree as possible, so that this important question is less dependent than previously upon the foreign fuel market.

Of course, some materials will have to be imported for the construction of wind power stations, essentially in the form of steel, copper and aluminum, but the currency demand for this will be earned back in approximately 2 years of electrical production by the wind power stations by the savings in the import of coal for the steam power stations.

About 80% of the costs of the construction of wind power stations will be wages and domestic costs, and here the matter includes the other social question, namely the employment question.

It is perhaps not very topical at the moment, but it has been in the past, and it can be again. The country has previously wasted large sums upon installation projects of /79
more, or mainly less, productive character out of regard for

employment and regulation of the job market. It would certainly be justified to build the wind power stations as a sort of reclamation project, which it is in reality, and to finance these projects in the same way as earlier land reclamation projects. In this case the price of wind electricity will probably always be less than the price of electricity from coal-driven stations.

Even though a strictly economic consideration of the installation of wind power stations was laid out, the price of wind electricity from these stations, to all appearances, will be less than the production prices from coal-driven stations built at the same time. In Fig. 27 it is shown how the price will be with various installation costs at 6 and 7% interest and amortization, respectively, plus an estimated amount for tending and maintenance.